FRAMEWORK FOR EVALUATING THE EFFECTIVENESS OF MONITORED NATURAL RECOVERY (MNR) AS A CONTAMINATED SEDIMENT MANAGEMENT OPTION

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ABSTRACT: Monitored Natural Recovery (MNR) of sediments is a risk management alternative that relies upon natural environmental processes to permanently reduce risk to the environment. MNR may be appropriate as a management alternative for certain sites or portions of sites, in part because it allows prioritization of response actions according to risk. A weight-of-evidence approach for evaluating MNR at contaminated sediment sites has been developed by the Remediation Technologies Development Forum (RTDF) Sediment workgroup. The approach includes steps such as data assessment, modeling, and site monitoring, to facilitate the assessment of MNR for contaminated sediment sites. The RTDF-Sediment MNR framework is intended to promote appropriate technical evaluation, increase the certainty, and provide decision makers greater confidence in the selection and implementation of this remedial option as a permanent, effective means of risk reduction. This framework employs established methods and accepted approaches that have been applied at a wide diversity of sites. Historically, implementation of MNR has been difficult in part because the science and methodology for comprehensive evaluation of the effectiveness of MNR has not been fully structured and developed. The framework, presented in this paper and supporting papers (Dekker et al., 2004; Erickson et al., 2004; Magar et al., 2004; Patmont et al., 2004), contributes to the development of science-based assessments of MNR in the remedy evaluation processes for contaminated sediment sites.

This working draft paper outlines a "weight-of-evidence" approach for evaluating the use of monitored natural recovery (MNR) for the remediation of contaminated sediments. This paper is one in a series of five papers proposing a framework, based on site-specific information, of five interrelated elements to assess the use and effectiveness of MNR. Developed by individual members of the Sediments Remediation Action Team under the Remediation Technologies Development Forum (RTDF), the papers are meant to serve as a resource to interested parties, but are not intended to be comprehensive or provide detailed information.

The five working draft papers represent the views of the authors and have not been subjected to EPA peer review. Therefore, it does not necessarily reflect the views of the EPA, and no official endorsement should be inferred. The working draft papers are not a regulation, and therefore, they do not impose legally binding requirements on EPA, States, or the regulated community, and may not apply to a particular situation based upon the circumstances. Interested parties are free to raise questions and objections regarding the "weight-of-evidence" approach provided in the papers. The RTDF Sediments Remediation Action Team is seeking and welcomes public comments on the papers. The papers are working drafts and may be revised periodically without public notice. Use or mention of trade names does not constitute endorsement or recommendation for use.

Introduction: Over the last century aquatic sediments in a variety of environmental settings have been contaminated as the result of chemicals released into the environment. For some of these sediments, once the source(s) of the chemicals are effectively controlled, the risks posed by the contaminants decrease with time due to naturally occurring processes. A wide range of physical, chemical, and/or biological processes may alter the concentration, mobility, toxicity, and/or bioavailability of chemical contaminants over time, and thus all contribute towards reducing risk reduction. The net result of processes that reduce potential risks to human health and/or the environment is referred to as natural recovery (Swindoll et al., 2000; Magar, 2001). When used as a risk management alternative, including confirmation of its protectiveness, this approach is known as Monitored Natural Recovery (MNR).

Assessments of the potential risks posed by environmental contaminants, including evaluations of risk outcomes resulting from implementation of a broad range of source control and remedial alternatives are key elements of risk-based decision making. These assessments and evaluations provide risk managers with details critical to selecting approaches that provide the greatest net environmental benefit. Careful and proper evaluation of the overall human health and ecological risk reductions associated with implementing different source control, containment, removal, and treatment alternatives poses many complex challenges and is often difficult to successfully achieve.

For many contaminated sediment sites, implementing a focused program of source control and, if appropriate, hotspot remediation may provide considerable environmental benefits, particularly where natural recovery processes are sufficiently developed to reduce risks within a time frame comparable to that required for more active risk reduction strategies. To properly evaluate such a course of action, sufficient information needs to be developed to allow for a technically defensible comparison of a wide range of potential remedial action alternatives including MNR.

Sediment MNR is a risk management option, which relies upon natural environmental processes to permanently reduce risk, and includes steps, such as careful assessment, modeling, and monitoring, to ensure success. To support the proper evaluation of MNR, sufficient data and information must be available to demonstrate that potential risks posed by contaminants are being alleviated to acceptable levels within an acceptable time frame. The acceptable contaminant level and acceptable time frame to reach this level will depend on site specific considerations. Typically, demonstration of MNR will be based on a weight-of-evidence approach, in which multiple lines of information contribute to an overall evaluation and conclusion. Specific evidence used to demonstrate MNR will be site and contaminant specific, but generally includes information on the source control and loading changes, long-term exposure trends, long-term sediment bed stability, and quantifying rates of those processes that are most important in reducing exposure levels over time.

MNR has been identified as one possible management option for addressing contaminated sediments (U. S. EPA, 1998, 2002). However, a framework and guidance for this option are lacking and are needed to improve management decisions. In addition, the information available to address the long-term effectiveness of MNR as a contaminated sediment management option in protecting human health and the environment is not widely available.

This paper presents a framework developed by members of the RTDF-Sediment workgroup for the assessment of MNR at contaminated sediment sites. The assessment of MNR and resulting risk-management decisions rely on a weight-of-evidence approach to evaluate and document risk reduction resulting from a combination of source controls and naturally occurring processes. In using this approach, it is assumed that an assessment of MNR would typically be conducted as a component of a broader assessment of the risk management alternatives for a contaminated sediment site. As such, preliminary assessment activities, such as site characterization and development of a conceptual site model, would normally have been conducted prior to the MNR evaluation.

As developed by members of the RTDF-Sediment workgroup, the framework for evaluating MNR includes five interrelated elements:

I. Characterize contamination sources and controls
II. Characterize fate and transport processes (both sediment and contaminant)
III. Establish historical record for contaminants in sediments (including bed stability)
IV. Corroborate MNR based on biological endpoint(s) trends
V. Develop acceptable and defensible predictive tools

The following discussion will focus on the specific components contained within each of these elements.

Element I: Characterization of Contamination Sources and Controls: A critical component in the evaluation of any sediment management option, including MNR, is to characterize historic and current contaminant loading to the sediment site (e.g., from watershed and point sources). Part of this understanding involves quantifying ongoing contaminant loading (e.g. mass releases over a finite time interval) to the site, and how such loading compares with historical releases. Because of the complexities often associated with contaminant loading processes, source characterization can be difficult and expensive. Thus, the level of effort required will be highly site-specific. Tools such as sediment trap deployments to collect recently deposited materials for chemical analysis may provide cost-effective methods of characterizing ongoing sources at certain sites.

Additional steps are often required to identify ongoing sources of chemicals to a site and support focused source control activities. It is often important in this evaluation to distinguish between contaminant sources that enter the site area proximal to the sediments being evaluated and those sources that are more regional in nature. It may also be helpful to distinguish in the evaluation between "external" upland/watershed sources that are a result of continued source activity (e.g. outfalls or non-point sources) versus "internal" sources associated with release from legacy sediments (e.g. resuspension of historical releases to the aquatic environment within the broad region being evaluated). These distinctions may be particularly appropriate if the boundaries of the site under consideration are not well defined. Quantification and characterization of internal contaminant sources to the water column from sediment release and resuspension is fundamental to the assessment of natural recovery processes. Internal contaminant sources are defined in this evaluation as those resuspension sources, including "hotspots", that may affect the quality of sediments located within the area where remedial action is being considered. Because these internal sources can act as a potential reservoir of chemicals that are continually cycled through the aquatic system, including biota, it can be important to characterize the nature and extent (e.g. spatial distribution) of such contaminant reservoirs, along with associated fate and transport process (see Element II below). This characterization could include quantifying internal contaminant sources to the water column from sediment release and resuspension. The goal of this assessment is to establish the mechanisms, rates, and spatial variation for these processes to provide adequate understanding for use in MNR.

Managing future risks requires accounting for the effects of ongoing sources. Future external sources can be very hard to predict and may be equally hard to control in the case of diffuse sources (e.g. atmospheric, groundwater, overland runoff, etc.). An assessment of the potential for these sources to impact recovery trends should be made and information compiled to allow an estimate of potential future loading activity from these sources. Regional data to support such evaluations is becoming increasingly available, often integrated into related total maximum daily loading (TMDL) analyses for watershed-based water quality decision-making.

Element II: Characterization of Fate and Transport Processes: Assessment of contaminant fate and transport processes in support of MNR requires understanding of environmental processes affect both sediment and contaminants (Magar et al., 2004).

Contaminant Fate: There are ranges of physical-chemical–biological processes which affect the fate and transport of sediment contaminants and the fraction of the contaminant that is bioavailable. These natural processes can, over time, alter the potential exposure of contaminants to sensitive receptors. Consequently, an effective MNR evaluation requires an understanding of the specific natural processes acting in the environment that affect the fate, mobility, and availability of the contaminant. Contaminant fate and transport processes need to be characterized and quantified to evaluate key processes affecting the spatial and temporal distribution of the contaminants in the area of interest, and to serve as a basis for predicting potential long-term exposure. These processes include burial, advection and dispersion, mechanical or molecular diffusion, partitioning, gas phase exchange, and abiotic and biotic transformation reactions.

Sediment Fate and Transport: Key processes affecting sediment transport include: erosion, flocculation and aggregation, settling/deposition, long-term burial, bed consolidation, biological and physical mixing in the bed, weathering and diagenesis of sediment particles, and bed sorting and grading processes arising from variations in flow velocity and transport capacity of the water column. Characterization of sediment fate and transport processes and long-term bed stability often require the understanding and quantification of chemical, water, and solid based processes (see Table 1).

Table 1.

Water-Based Processes	Solids Processes	Chemical Processes
Area hydrology (overland flow, runoff, CSO discharges, dam operations)	Settling/Deposition/ Consolidation/Burial	Partitioning to organic carbon and colloids/Sequestration

Surface water hydraulics/hydrodynamics (streams/ lakes/ estuaries):	Scour/Resuspension/Bed Load Transport	Biodegradation/bio-transformation
Pore water flow/Dissolved-phased sediment-water chemical transfer rates (often strongly biologically-mediated)	Primary production (algal and macrophyte contribution to sediment budget and deposition)	Bioturbation /bioirrigation
Groundwater flow rates		Oxidation/reduction (redox)
Surface water flow velocities and shear stresses at sediment surface	External loading (tributaries, boundary loading in estuaries, upstream, etc.)	
Historical flow and tide stage records		

Characterization of these processes as outlined in Table 1 should be appropriate to the size and scope of the investigation. To this end a tiered approach to collecting data and information may be implemented (Table 2). A Tier I investigation would include developing an understanding of key relevant processes using existing data. As needed a Tier II investigation would include a more detailed understanding of relevant processes, mechanistic approaches, supported by field investigations.

Table 2: Examples of Tier I and Tier II approaches in characterizing different processes

Process		**Level of Process Description** ***Tier I Analysis***	***Tier II Analysis***
Water	Hydrology	Simple runoff calculation/ unit hydrograph/ rational method	Detailed runoff model, GIS land-use characterization
	Surface Water Hydraulics	One-dimensional hydraulics, possibly extreme event simulations	-
	Surface Water Hydrodynamics	-	Two- or 3-d description of hydrodynamics, including extreme flood/wind events
	Groundwater Flow	If needed, analysis of regional gradients, gaining/losing portions of stream	Description of groundwater-surface water interaction, possibly with model representation
	Pore Water Flow	Simple bracketing calculations of estimated pore water inflow	Field measurements (bag studies), groundwater-surface water processes explicitly represented, linked by pore water flow
Solids	Deposition/Consolidation/Burial/ Resuspension	Empirical relationships used to estimate potential for resuspension/ deposition	Field measurements, mechanistic representation of deposition, resuspension, consolidation and burial processes
	Vertical mixing	Estimated based on available core data	Field measurements, including radioisotope data and analysis
	Primary production	Estimated based on common production rates	Site-specific estimates based on chlorophyll-a, measured solids
	Advection	One-dimensional estimate	Field data collection, two or three-dimensional representation of surface water velocities
	Bioturbation	Estimate based on book values	Collect site-specific data
	Decay	Estimate based on book values	laboratory sorption studies on actual sediments to quantify rate, extent of decay/transformation
Contaminants	Advection/dispersion	Base on one-dimensional flow field	Field data collection, two or three-dimensional representation of surface water velocities and mixing processes
	Partitioning	Estimate based on book values	Laboratory sorption studies on actual sediments to quantify rate, extent of partitioning.
	Decay/transformation	Estimate based on book values	Laboratory sorption studies on actual sediments to quantify rate, extent of decay/transformation
	Volatilization	-	Use literature estimates of volatilization rates
	Diffusion	Estimate based on book values	Estimate based on book values, assess via calibration of detailed process model
	Biological processes	Simple biota-sediment accumulation factor (BSAF) approach	Process-based bioaccumulation model

Information on sediment stability is necessary to assess the long term integrity of the sediment bed and understand the effects of rare, extreme event conditions on contaminant and sediment mobility. Evaluation of MNR often requires assessing the long-term stability, to insure contaminant isolation under normal and relatively extreme hydrodynamic events that can cause elevated erosional conditions (e.g., the 100-year return frequency events). Evaluation of future bed stability can be conducted in a number ways, generally involving inference from empirical evaluation of historical data, and/or prediction based on development of deterministic models that are both consistent with historical data and capable of providing a fairly accurate representation of extreme event stresses and sediment transport. When sediment stability assessment indicates no historical evidence of instability and no significant potential for future resuspension, this information is critical for evaluating MNR as a permanent remedy for risk reduction.

Empirical evaluation of sediment stability generally includes a quantitative geomorphic assessment of the site to understand long-term cause/effect behavior of the watershed and aquatic system processes on sediment stability. A historical review of relevant information for the site, including data collection to obtain information "recorded" in sedimentation profiles, can be conducted to provide quantitative information on long-term sediment dynamics or geomorphology. This approach coupled with a review of historical hydrodynamic records can indicate whether the observed historic record reflects impacts of past extreme events. When adequate data is available, sediment (and potentially associated contaminant) transport models can be developed to predict sediment transport and long-term bed stability including an extreme event. Defensible model development requires the model predictions are consistent with available historical information for the site. This information can be compiled in a weight-of-evidence demonstration of sediment stability. Erickson et al. (2004) present a proposed weight-of-evidence framework for sediment stability assessment as a component of the RTDF-Sediment MNR Framework.

Element III: Establish Historical Record for Contaminants in Sediments: The primary objective of this element is to evaluate reduction in chemical exposure using temporal trends in sediment chemical data. Chemical concentration data assembled from past sampling events can be used to establish a historical record for contaminated sediments. These temporal trends can be used to assess whether statistically significant reductions in chemical concentrations have occurred in surface sediments. However, it is important when establishing these trends to evaluate the quality (e.g. QA/QC) of the data. This QA/QC evaluation could involve comparing techniques for different sampling events, sample locations, as well as comparing detection limits among the different events and laboratories.

Historical trends in contaminant release to a site can also be inferred from sediment core analyses (Brenner et al., 2004; Magar et al., 2002). This approach also provides information on temporal record of sediment deposition as well as history of contamination and weathering at a site by viewing and analyzing vertical sediment profiles. Sediment cores, collected in depositional area, are vertically segmented, with the contaminant concentrations determined in representative segments to establish a vertical contaminant profile. Coupling the vertical contaminant profile with radio-geochemistry dating (e.g., ^{7}Be, ^{210}Pb , ^{137}Cs) to delineate time stratigraphic intervals can provide valuable information as to the temporal variations of contaminant release to the site as well as providing information on the age of sediment deposits, sediment accumulation rates and surface mixing depths. These analyses can help establish vertical contaminant concentration trends and can be used to determine whether contaminant profiles show decreasing surface sediment concentrations. Age dating results can be combined with contaminant concentration profiles to estimate the time required to meet surface sediment target concentrations (Brenner et al., 2004; Magar et al., 2002) and can help reduce uncertainty in future predictions of MNR. That is, sediment cores provide information about the age of sediment deposits, history of sediment contamination at the site, source control effectiveness, sediment accumulation rates, and the recovery of surface sediments, all of which can be used for the informed design of a sediment recovery/management program.

The vertical distribution of contaminants also provides insight on the fate of the contaminants in the sediment. For example, the impact of specific transformation processes (e.g. biodegradation) can be estimated based on the vertical profile of the breakdown products in the sediment cores (Magar et al., 2002; Stout et al., 2001). Comparison of chemical data (e.g., congener profiles or PAH chromatograms) among sediment segments can be used to establish contaminant weathering patterns with sediment depth and age.

Natural capping of clean sediments atop contaminated sediments can also be assessed using sediment cores and vertical contaminant profiles. Following implementation of effective source controls, surface sediment concentrations have been observed to asymptotically approach area background levels over time at sites where there is deposition of clean, or increasingly cleaner sediment (Patmont et al., 2004; Magar et al., 2002, 2004; Brenner et al., 2004). Benthic and hydraulic mixing, as well as contaminant fate processes, control the rate of the asymptotic-like approach to area background levels, and determine whether years or decades are required for surface sediments to meet risk-based benchmark concentrations.

Element IV: Corroborate MNR Based on Biological Endpoint(s) Trends: The objective of Element IV is to confirm that risk reduction, as may be indicated by evaluation of chemical conditions under Element III, is corroborated using relevant biological measurements (Patmont et al., 2004). In many sediment site risk assessments, biological endpoints serve as the primary line of evidence for assessing human health and/or ecological protection. Depending on the specific site conditions, particularly relevant data often include fish and invertebrate monitoring of key biological endpoints such as tissue chemistry/residues, histopathology/biomarkers, acute and/or chronic sediment toxicity bioassays, and community analysis. The relevance/appropriateness of the endpoints are likely to be defined in the site-specific risk assessment. Similar to Element III, in this analysis it is important to consider whether there are adequate, comparable biological endpoint data available to support an evaluation of temporal trends.

Establishment of historical trends should include sampling sufficient to provide adequate statistical evaluations of temporal trends of the biological endpoint of interest. Specifically, data should be available for a time period over which recovery could be expected, considering such factors as the life cycle and age of the biological community(ies) being addressed. Also, timing of sampling events, and number/location of samples collected can have a significant impact on the confidence in the trend analysis.

Potential confounding factors to trend analysis with biological endpoints include potential differences in field collection methods for different sampling events, laboratory analytical protocols, population dynamics, fish migration patterns, food chain dynamics as well as spatial variation in habitat quality, organism density, organism lipid content, age, sex, size, reproduction cycles, and seasonal variations in abundance or condition. However, with careful study design and evaluation, many of these confounding factors can be minimized.

Using appropriate data sets, trend analyses of relevant biological endpoints can often be used to corroborate risk reductions and biological recovery as may be indicated by chemical data. However, statistically valid methods for testing the significance of identified trends (parametric, non-parametric tests) need to employed only after testing, controlling for other potential confounding factors.

Element V: Development of Acceptable and Defensible Predictive Tools: The final, critical step in documenting the potential for MNR as a management alternative is to evaluate whether the observed reductions in sediment and biological risks can reasonably be expected to continue into the future. Future forecast of MNR effectiveness is most often accomplished though the use/development of predictive tools such as numerical models. In systems in which fate and transport processes driving recovery may be complex and may change with time, simple extrapolation of historical trends may not be appropriate. In such cases, a well-constructed numerical model can be a useful tool to predict future behavior of the system (Dekker et al., 2004) in support of a MNR evaluation at a sediment site. These predictive tools can be used to evaluate changes in both the biota and sediment quality resulting from different management alternatives.

The role of predictive tools in evaluating MNR is to integrate empirical data to provide process-level understanding of natural recovery through calibration to multi-media data. This analysis involves computing reductions in exposure due to combined effects of natural transport processes, bio/chemical degradation, and contaminant loadings and predicting sediment erosion/stability during extreme events in order to evaluate long-term permanence of MNR. The fundamental aspects of forecasting MNR require: 1) sufficient measurement or observation of key process rate coefficients, 2) calibration to long-term trends, and 3) reasonable confidence that future conditions will be similar to conditions during model calibration, or a means to account for changes, such as those in sediment loading due to watershed changes.

Different types of predictive tools can be implemented for forecasting MNR and these approaches can be categorized into a set of progressively more complex tiers. The choice of tool application will largely depend on the size and complexity of a site. The types of tools available to help describe and predict a systems behavior include:

- Tier I - Empirical trend analysis and forecasting of future declines in bioavailability based on water, sediment, and biological data (i.e. Element III and IV).
- Tier II - Calculation of characteristic attenuation rates based on determination of key attenuation process coefficients and forecasting from current sediment concentrations.
- Tier III - Mass balance modeling of sediment bed and overlying water.

- Tier IV – Integrated mechanistic hydrodynamic, sediment transport, contaminant fate and transport models

Summary: To successfully implement MNR as a risk based management option it is important to identify and assess those processes that contribute to risk reduction. To this end, a framework for assessing the appropriateness of MNR as a risk-management alternative has been developed by members of the RTDF-Sediment workgroup. The assessment processes are technically robust and utilize multiple lines of information to assess the fate and transport of sediment contamination and the potential for future risk reductions.

To support the selection of MNR, it must be adequately demonstrated that potential risks posed by contaminants are being alleviated to acceptable levels within an acceptable time frame. The acceptable contaminant level and acceptable time frame to reach these levels will depend on site-specific considerations and regulatory concerns. Most assessments of MNR will require a weight-of-evidence approach, in which multiple lines of information contribute to the overall evaluation and conclusions. Specific evidence used to demonstrate MNR will be site and contaminant specific.

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